Wind Engineering Joint Usage/Research Center
FY2022 Research Result Report

Research Field: Indoor Environment
Research Year: FY2022
Research Number: 22222007
Research Theme: Study on Multi-vent based Adaptive Ventilation (MAV) for demand-oriented indoor environment

Representative Researcher: Weirong Zhang

Budget [FY2022]: 600000 Yen

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1. Research Aim

To further create a healthy, efficient, and comfortable indoor environment, variable dynamic ventilation is proposed to regulate and control the indoor environment from the perspective of ventilation construction. There are multiple indoor air distribution methods, including mixing ventilation (MV), displacement ventilation (DV), and underfloor air distribution (UFAD), even personalized ventilation (PV). These ventilation systems still need to be predesigned and operated using a fixed flow pattern upon installation. Once the design of the air terminal system is determined, the ventilation system cannot be changed in subsequent application. In other words, indoor airflow is not adjustable.

Owing to these limitations, multi-mode ventilation (MMV) (Shao X, 2017) systems with several single airflow patterns were proposed. For the system, it is the combinations of single airflow pattern can address one or more typical scenarios effectively. But the schemes it offers are still limited by fixed vents. A later study developed an adjustable fan network (AFN) system using fan diversion (Huan Wang, 2020). AFN can change the airflow pattern based on the ventilation requirements. Meanwhile indoor layout tends to be open and shared, emphasizing the diversification of functions, however, the previous ventilation methods lack of adjustability and adaptability to different environmental demands. There is a gap in terms of a proper air terminal system that can provide flexibility and adaptability for real applications.

Therefore, there are problems with refining:

1. When indoor demands change, whether there is or how to develop a novel ventilation control solution to adapt to a wider range of daily occasions.
2. If there exists a ventilation solution with superior adaptability and easy adjustability, how to determine the suitable vents scheme from the demand side?

To solve above problems, this study proposes a novel air terminal system- multi-vent based adaptive ventilation (MAV) system that comprises multiple ventilation modules. The proposed system can change the vents schemes according to demands by a reversing device. Study on the effect of MAV to reduce cross-contamination has been published recently [1]. And the decision-making analysis of ventilation strategies under different situations was studied in our pre-sequence work [2]. The basic idea of MAV system hinges on using multiple small vents to create different airflow patterns based on the ventilation demand. The emergence of MAV can be used as a suitable air terminal system for demand-oriented ventilation.

2. Research Method

To meet the requirements of occupants and maintain good indoor air quality, a dynamic multi-vent ventilation module was proposed by Zhang et al., and its effect on the contaminant diffusion control was evaluated first (Zhang et al. 2022). A schematic diagram of the configuration is shown in Fig. 1. Details of the system configuration can be found in Reference by Zhang et al. (2022).

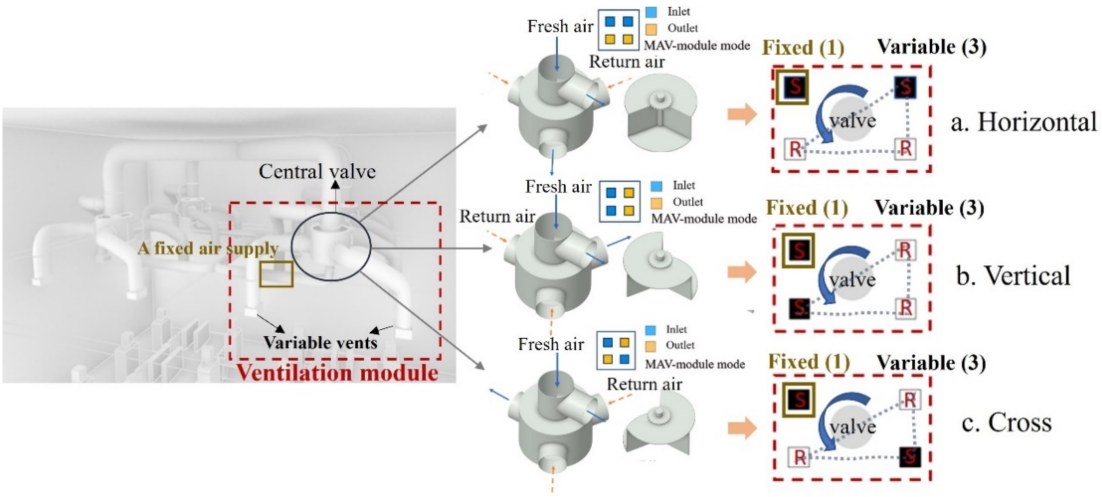


Fig. 1 Schematic diagram of three different ventilation schemes (S : Supply ; R : Return)

A major innovation is the design of the central valve. The valve can realize the inlet-outlet switching function, and then they are combined to complete the switching of the ventilation schemes, which greatly adapt to different indoor scenarios. With this central valve, each ventilation module has three schemes, which can realize the switching of the air duct through the rotation of the rotor. If this module is arranged independently, personalized control in a small scope can be fulfilled. A systematic arrangement can provide suitable solutions for environmental control in typical scenarios.

Like MMV, MAV is not a new airflow pattern. In essence, MAV is a special form of MV, which has been further developed to adapt to multiple scenarios and control the local indoor environment. MAV uses concentrated vertical jets to produce downwards airflow. The flexibility and locality of control are the most significant advantages of MAV, compared to MV and MMV. MAV has these advantages: MAV can realize zoning control by forming small air circulations and protect the local thermal environment and reduce the spread of contaminants. Vents can be switched to be inlets or outlets in a MAV module to meet with scenarios demands flexibly. It can reduce discomfort caused by continuous blowing in local positions. There are disadvantages. Current ventilation module structure is complex and occupies more upper space. It is hard to control the air volume balance during the air flow switching process of the central valve in the box.

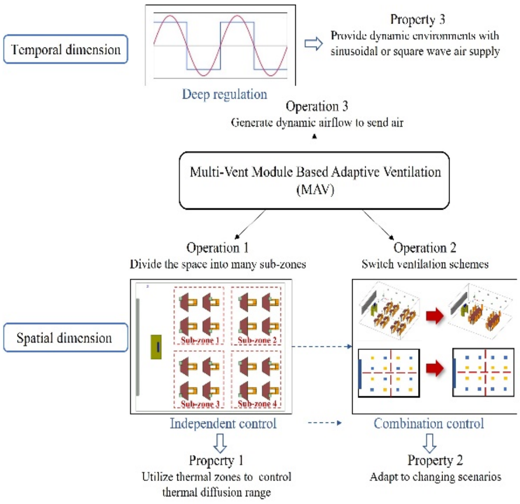
The basic idea underlying MAV aims to emphasize the optimization strategy to respond to different demands and scenario changes flexibly.

The modular design of MAV intends to control the local thermal environment and local air quality in dividing the whole space into multiple sub-zones and forming small air circulations, and it can effectively protect the local thermal environment and local air quality from the surroundings. Another key feature is that the number of MAV vents are larger and the distance between inlet and outlet is closer than MV. The smaller distance between the air inlet and the outlet makes the air circulation smaller. Since the airflow here was concentrated and directed vertically into the breathing zone, the disturbance brought by MAV to ambient air is less than that produced by a MV diffuser. That means that when contaminants are released from a certain position, they do not have to travel through a large cycle to be exhausted, but can be controlled in a small range. Therefore, heat and contaminants could be removed nearby. Through the exchange of the vents, the vent solutions become diverse; therefore, the system can adjust and optimize the air distributions to adapt to multiple scenarios and guarantee different needs.

3. Research Result

3.1 Effective improvement of a local thermal environment using multi-vent module-based adaptive ventilation

To verify the three-level control effect of MAV in improving thermal environment, as shown in Fig. 1, simulations were conducted. A numerical study based on a multifunctional classroom (10.0 m (length) × 8.0 m (width) × 3.0 m (height)) was conducted under four scenarios, as shown in Fig. 2. There were 16 occupants distributed in a sedentary state, and a computer on the podium. Four ventilation modules were designed in the room to study the effects of individual and combined use. Therefore, there were 16 vents. The size of small vents was 0.20 m ×0.20 m, and they could be switched as either inlets or outlets by using a rotor. Cases were set under MAV and MV systems, totally 8 cases, as shown in Table 1.



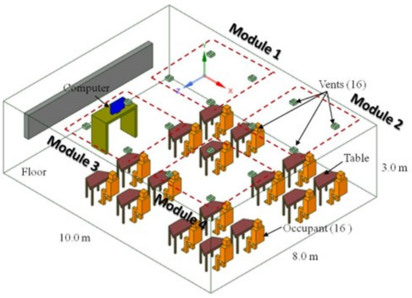
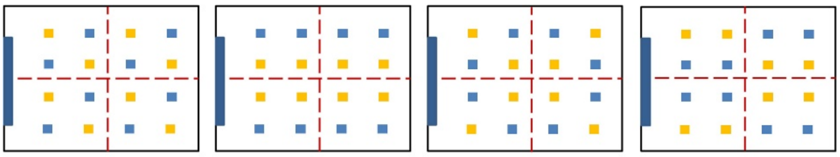
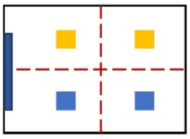


Fig. 1 Structure of MAV control characteristics **Fig. 2** Geometry of the classroom (General)



(a) Uniform (b) Sideway (c) Annular (d) Compound



(e) Vent scheme under MV

Fig. 3 Response of ventilation schemes to changing scenarios

Table 1 Case setup

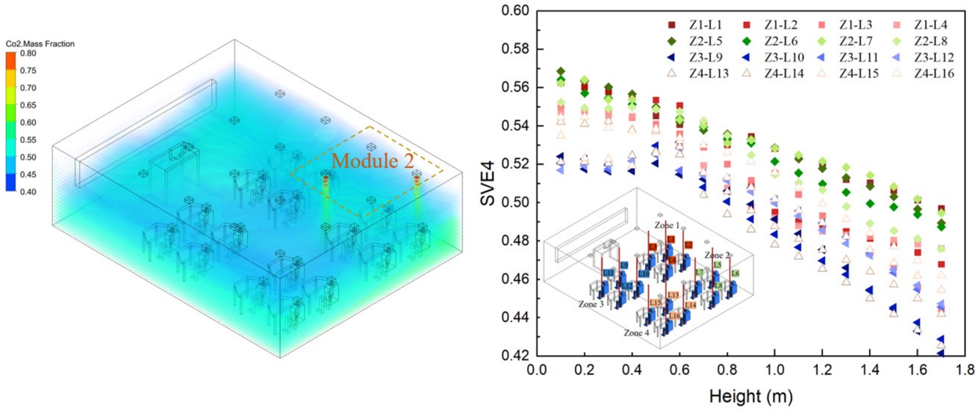
Case No.	Air distribution	Scenario	Vent scheme
1	MAV	a. General	Uniform
2		b. Discussion	Sideway
3		c. Meeting	Annular
4		d. Debate Competition	Compound
5	MV	a. General	-
6		b. Discussion	-
7		c. Meeting	-
8		d. Debate Competition	-

The metric in local zone control comes from the scale for ventilation efficiency No.4 (SVE4) defined by S. Kato (1988). To know the thermal comfort level of occupants when MV and MAV are applied in different scenarios, the criteria used to evaluate overall and local thermal comfort are air diffusion performance index (ADPI), predicted mean vote (PMV), and draught rate (DR).

3.1.1 Zoning control

SVE4 is used to quantify the zoning division of MAV. SVE4 shows the influence range of the air supply inlet, which indicates the amount of air blown from the air supply inlet as the object of the study reaches a specific point when a room with multiple air supply diffusers is studied. Fig. 4 shows the results of SVE4. The concentration of CO2 is used to characterize the influence degree of the supply air. Four sampling lines are selected in each sub-zone, a total of 16. The four legends represent four sub-zones respectively, and the same color is used to represent the points in a sub-zone.

SVE4 in sub-zone 2 ranges from 0.48-0.57. It can be found that SVE4 in zone 2 is higher than others, which indicates that when the air supply of Module 2 is marked, it has a greater influence on zone 2 below Module 2. Sub-zone 3 and 4 are less affected by this supply air. And the SVE4 difference between sub-zones increases with the increase of height. This is consistent with the result in Fig. 4(a), that is, the closer to the air supply inlet of Module 2, the greater the value of SVE4.



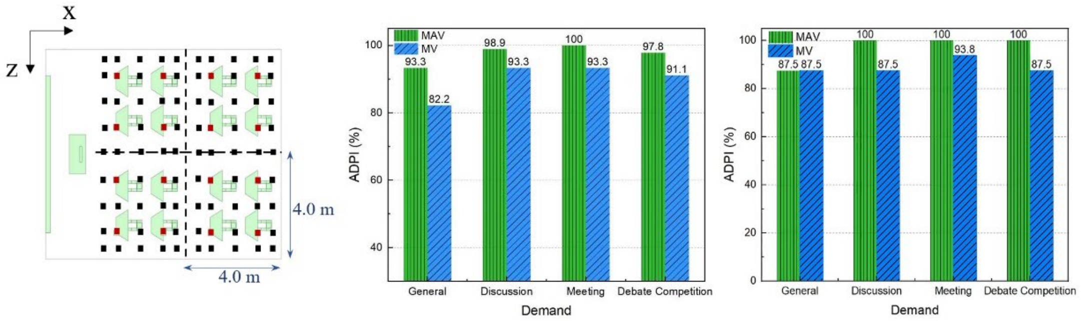
(a) Volume concentration when the supply air (b) Detailed SVE4 distribution in Module 2 is monitored

Fig. 4 SVE4 under MAV (taking Module 2 as an example).

By this verification, the modular system can play a role in a non-uniform indoor environment oriented to local requirements, and when the local load exists, the corresponding module can achieve local control by forming small air circulations.

3.1.2 Improvement of thermal comfort

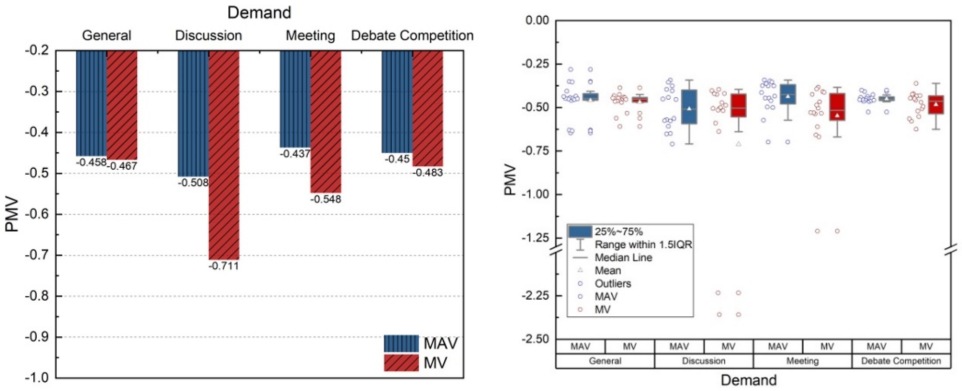
Fig. 5 presents ADPI results from two measuring points. It can be seen from ADPI results that the all cases are all higher than 80%. ADPI of MAV is higher than MV under various demands. In terms of pursuing better thermal comfort, MAV conditions are better than those under MV. In Fig. 5(b), the difference between two modes is more significant, up to 11.1%. If the points are taken in front of each occupant, ADPI in each case is also higher than 80%. Combining the results under two points selections, MAV is superior to MV in terms of the overall thermal comfort performance.



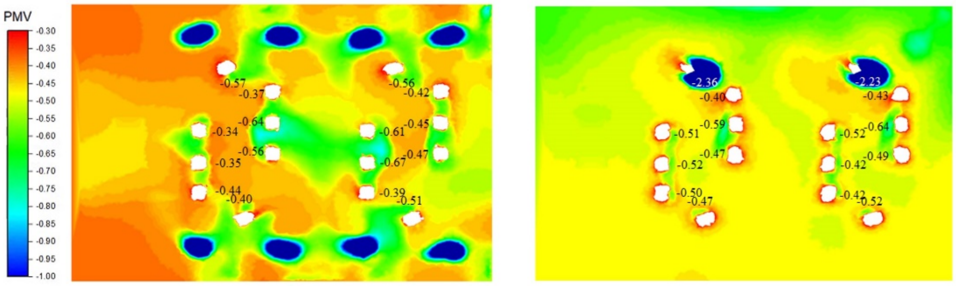
(a) The locations of the fixed points (b) ADPI based on fixed points (c) ADPI based on occupants' locations

Fig. 5 ADPI results based on two kinds of points

PMV results are shown in Fig. 6. The averaged PMV in the MAV mode is higher than that in the MV mode and closer to 0 under each demand. The maximum difference between these modes is 0.207. In Fig. 6(b), more points are distributed concentrated above -0.5 in the MAV mode, while there are fewer points in the MV mode and some outliers appear. The overall distribution in the MAV mode is indicated by a redder color, indicating better thermal comfort, as shown in Fig.6 (c)-(d). Similarly, DR shows similar results.



(a) The average PMV results (b) Detailed PMV distribution

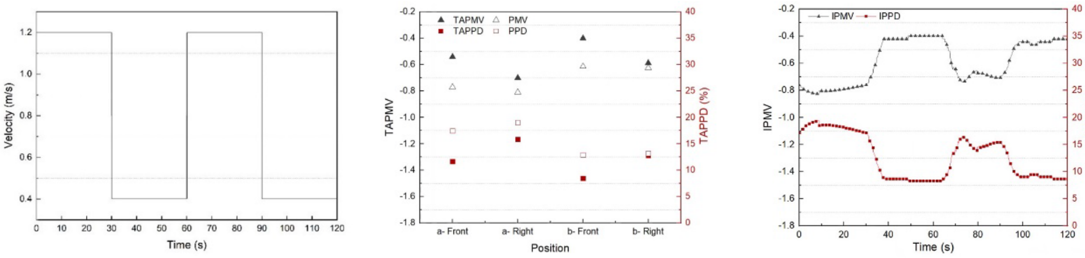


(c) PMV distribution in MAV under scenario B. Discussion (d) PMV distribution in MV under scenario B. Discussion

Fig. 6 PMV results

To further explore the possible reinforcement of MAV with dynamic pulsating airflow, we selected two occupants as research objects and implemented dynamic airflow to the terminals above them to observe the differences under the condition of constant air supply.

Fig. 7 shows the comparison of PMV-PPD results under constant and pulsating air-supply conditions. The results show that compared with steady air supply, the TAPMV and TAPPD of these positions are improved under the pulsating air supply.



(a) Variation of supply air velocities with time

(b) Comparisons of PMV-PPD under steady and pulsating air supply

(c) IPMV and IPPD results for No. b- Right

Fig. 7 Thermal comfort results with dynamic air supply

As an innovative attempt of variable dynamic ventilation strategies, from the results brought by the changes, MAV outperforms traditional MV in local thermal environment control and creates better thermal comfort. The concept of MAV can be regarded as a new way to expand adaptive ventilation and is also expected as an efficient air distribution pattern for different HVAC applications.

3.2 Evaluating the effectiveness of multi-vent module-based adaptive ventilation for protecting room occupants from infection using a novel design parameter

Multi-vent module-based adaptive ventilation (MAV) is a novel type of ventilation that facilitates the switching of inlets and outlets to suit different indoor scenarios without changing the ductwork layout. However, little research has been undertaken to evaluate the sizing of MAV modules and selection of air velocity, both of which are related to the efficiency of the MAV system in removing contaminants and the corresponding level of protection for occupants in the ventilated room. Therefore, this study proposed the module-source offset ratio (MSOR) based on the size of the MAV module and its distance from an infected occupant to inform the selection of the optimal MAV module parameters accordingly.

3.2.1 MAV design parameter

Modern mixing ventilation design typically considers thermal comfort to arrange the inlets and outlets, and while the adequacy of airflow mixing is considered, controlling the diffusion of contaminants is not the primary design target. Local ventilation at the source of contamination represents an excellent method for controlling the spread of contaminants, but its practical application in the office environment remains difficult. The MAV allows a room to be divided into sub-zones using multiple MAV modules comprising inlets and outlets, reducing the distance from the contaminant source to the nearest air outlet. In addition, the interchangeable inlet and outlet vents in each module can be adapted to the locations of different contaminant sources. The effectiveness of MAV in controlling the diffusion of contaminants can be influenced by many different factors, such as the size of the MAV module or location of the contaminant source. Oversized MAV modules will have essentially the same effect as conventional mixing ventilation, whereas undersized MAV modules will require a denser distribution of vents that not only results in excessive construction costs, but can increase the occupants' sensation of draught, which is not conducive to creating a comfortable indoor environment. This study therefore proposed a new MAV module design parameter that combines the location of the contaminant source relative to the module with the absolute size of the module to obtain the value most conducive to contaminant diffusion control in different scenarios.

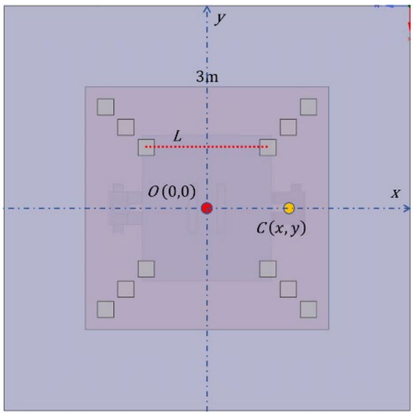


Fig. 8 Schematic of MAV design parameters.

As shown in Fig. 8, the four air vents of an MAV module are often arranged in a square, with their centre point taken as O at the coordinates (0,0). The location of the contaminant source C is expressed using the coordinates (x, y), representing the distance from C to the two axes in constant, positive values. The value L represents the length of the line connecting two adjacent air vents, which is also used to represent the absolute size of the MAV module. The dimensionless design parameter for the MAV module, the module-source offset ratio (MSOR), is therefore defined as follows:

$$MSOR = \frac{2s}{L}, \tag{1}$$

where $s = max(x, y)$, indicating the largest offset of the source from the origin O. When MSOR = 1, the contaminant source is immediately below the line connecting the two vents, when MSOR < 1, the contaminant source is inside (on the O side of) the line connecting the vents, and when MSOR > 1 the contaminant source is outside the line.

3.2.2 Principles of MAV control effect evaluation

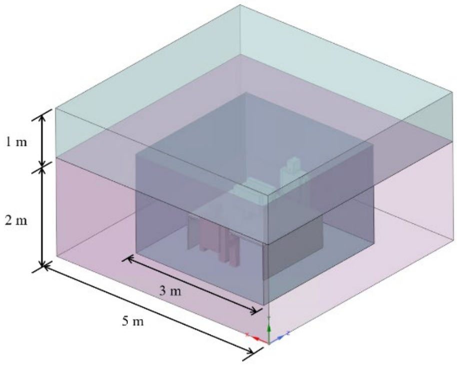


Fig. 9 Illustration of the spatial zoning method.

The key function of the MAV is to divide the room into sub-zones and reduce the diffusion of contaminants between them. To provide this functionality, the following principles must be followed when carrying out any MAV performance evaluation.

Principle 1: The highest priority for the MAV module is to prevent the spread of contaminants outside the module control area, even though this may increase the risk of infection for healthy occupants within the module control area. In offices, the risk of infection is already higher for those in close proximity to an infected person, especially when they are face-to-face, as demonstrated in the authors' previous study [25]. Ensuring that contaminants do not spread and affect the occupants in less vulnerable locations in the room is therefore the critical priority.

Principle 2: Contaminants in a work area within the module control area should be exhausted as quickly as possible to control their spread. This can also minimize the risk of infection to healthy occupants within the module control area.

Principle 3: Contaminants are best discharged through the return air outlet, though suspension in the area above the occupied zone is also acceptable.

The distinct locations of particles represent particularly critical information required to accommodate these three principals. The simulation area considered in this study was assumed to be part of a larger office; therefore, the wall around it can be understood as a simple partition dividing this small space from the larger space. The simulated room was divided as shown in Fig. 9 into three zones: the area above 2 m in height; the area below 2 m in height but located in the inner part of the simulated area; and the area below 2 m in height but located in the outer part of the simulated area. The dimensions of the inner part of the room were set to 3 m × 3 m.

Given the three room zones defined above, a contaminant particle can eventually be: exhausted by the outlets, captured by the ceiling or side walls above 2 m, suspended in the zone above 2 m, suspended in the inner zone, captured by occupants and furniture in the inner zone, suspended in the outer zone, captured by the outer walls below 2 m, and captured by the ground. As the objective of MAV is to control the dispersal of contaminants, all particles in this study were classified as non-threatening, potentially threatening, or escaped. Non-threatening particles are those that are located above the room and are about to be exhausted. Potentially threatening particles still have the potential to spread out of the area or stick to surfaces that are accessible to an occupant, thereby representing a risk of airborne or contact transmission to those inside and outside the module control area. Escaped particles have spread beyond the MAV module control area. This study considered the particles exhausted by outlets, suspended above 2 m, and captured by the floor to be non-threatening. Particles captured by furniture surfaces in the inner zone or suspended in the inner zone still presented a potential threat. Particles captured by external walls below 2 m and particles suspended in the outer zone below 2 m were considered to have escaped.

3.2.3 Droplet diffusion characteristics over time

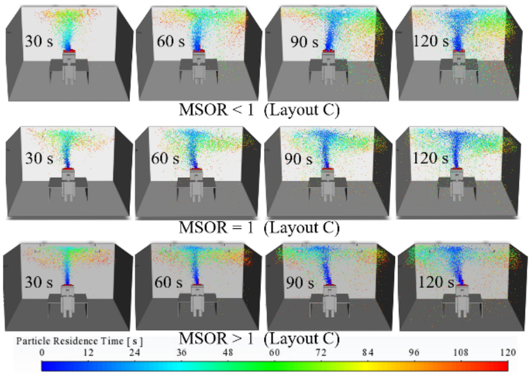
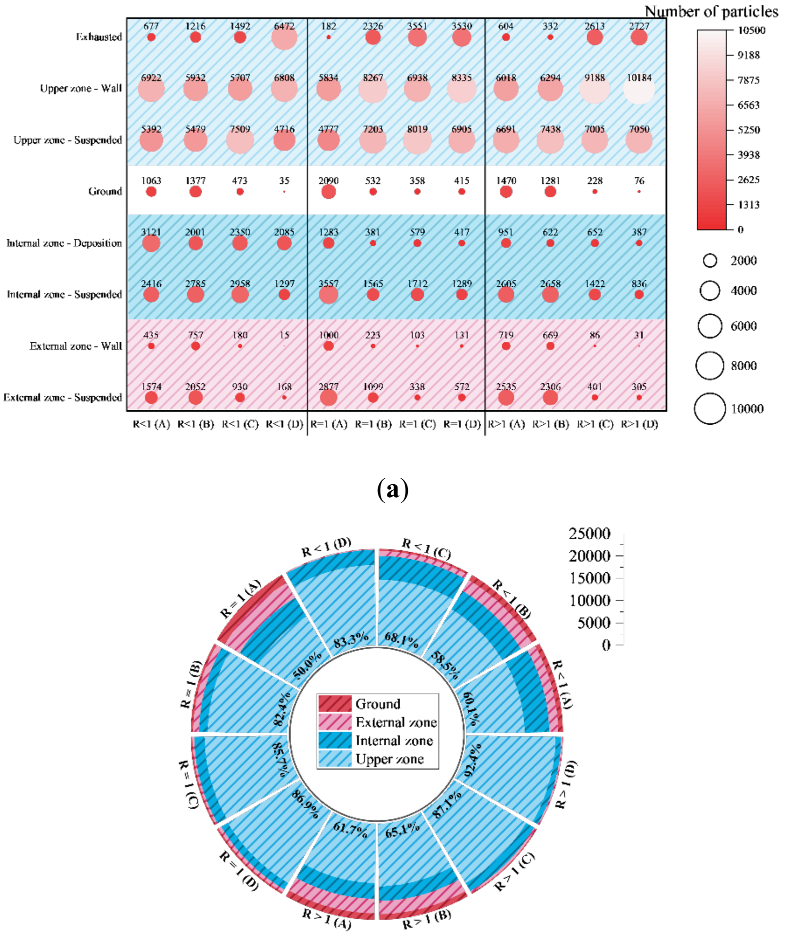


Fig. 10 Variation of particle distribution over time for three different MAV design parameters *MSOR*.

Fig. 10 shows the variation of particle distribution over time at a supply velocity of 1.5 m/s for three MAV design parameter MSOR values using layout C, as considered in Cases 7, 19, and 31. As shown in Fig. 10, following its release from the infected occupant's nostrils, the low velocity and flow rate of the contaminant hinder its ability to maintain its original flow direction and result in its rapid ascent. The upward movement of the contaminant is primarily driven by two factors: the upward buoyancy generated by the heat plume surrounding the human body and the lift produced by the temperature difference between the exhaled airflow and the indoor air currents. This result confirms the conclusion obtained in former section indicating that in MAV systems, the thermal plume significantly influences contaminant dispersion when the initial momentum of the contaminant particles is low. From the moment the contaminants are expelled through the nasal cavities of infected individuals, they are released and begin to rise. Within 30 s of release, the contaminants reach the ceiling and disperse in all directions. Observations indicate that as the MSOR value increases, so does the range of dispersion. From 30 to 60 s, the contaminants continued to diffuse outwards. From 60 to 120 s, when MSOR < 1, the contaminants were entrained by the airflow and blown downwards owing to the close horizontal distance from the air inlet to the infected person, which is considered harmful to the health of other occupants in the inner zone; when MSOR > 1, the vents were more widely spaced and therefore the particles were dispersed over a larger area, making the MAV module less effective in controlling the dispersion of contaminants. However, the ceiling can trap particles, and such trapped particles are not shown in the diagram, which shows only the particles suspended in the air.

3.2.4 Final fates of particles at different layouts, and MSOR values



(**a**)

(**b**)

Fig. 11 Particle distributions at 1.5 m/s air supply velocity: (**a**) distribution of the number of particles at different *MSOR* values according to MAV layout and (**b**) percentage of particles in the different room zones.

Comparing the results for different MSOR values in Fig. 11(b), the number of particles in the upper zone is clearly smaller when MSOR < 1 than when MSOR = 1 or MSOR > 1, whereas the number of particles in the inner zone is significantly larger. The bubble matrix in Fig. 11(a) indicates that this occurred because more particles were captured on the table and occupants at this MAV module size owing to the closer distance between the vent and the occupant, which allowed the jet to entrain a portion of the particles back into the inner zone. This situation will increase the risk of infection to other occupants within the MAV module control area. When MSOR = 1, Layout A did not perform well, but Layouts B, C, and D all exhibited a safe zone particle count in excess of 82%. Although the number of particles in the outer zone did not increase significantly compared to the case when MSOR < 1, the increased distance between the vents enabled the contaminants to move upwards more readily, facilitating their smooth entrance into the safe zone. When MSOR > 1 a small increase was observed in the number of particles in the outer zone owing to the larger vent spacing, which left a gap in the outlet control area that resulted in a portion of particles entering the safe zone without being exhausted and subsequently escaping from the safe zone. This is exemplified by the particle distribution when MSOR > 1 in Fig. 10.

The difference between the various MAV layouts became more obvious as the air velocity increased. For Layout A, the two inlets located above the infected occupant inhibited the effectiveness of the MAV, whereas for Layout D, the two outlets above the infected occupant consistently performed excellently. Meanwhile, the axisymmetric air vent arrangement for Layout B performed poorly compared to the centrosymmetry of Layout C, with the former exhibiting a 3–9% reduction in the number of particles in the safe zone.

4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

1. Haotian Zhang, Weirong Zhang*, Weijia Zhang, Yingli Xuan, Yaqi Yue. Multi-vent module-based adaptive ventilation to reduce cross-contamination among indoor occupants[J]. Building and Environment, 2022, 212: 108836.
2. Weirong Zhang*, Yanan Zhao, Peng Xue, Kunio Mizutani. Review and development of the contribution ratio of indoor climate (CRI)[J]. Energy and Built Environment, 2022, 3(4): 412-423
3. Weijia Zhang, Weirong Zhang*, Haotian Zhang, Yingli Xuan, Xuebiao Liu. Numerical study on the thermal performance for multi-vent module based adaptive dynamic ventilation [J]. Building Simulation, 2022

[Presentations at academic societies]

1. The 16th ROOMVENT CONFERENCE, ROOMVENT 2022: Study on the thermal performance under the implement of multi-vent module-based adaptive ventilation. September 16 to 19, 2022. (Reporter: Weijia Zhang)
2. The 16th ROOMVENT CONFERENCE, ROOMVENT 2022: Study on vent spacing of multi-vent module-based adaptive ventilation for reducing contaminant diffusion. September 16 to 19, 2022. (Reporter: Haotian Zhang)

[Published books]

1.
2.

[Other]

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5. Research Group

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2. Weijia Zhang, Beijing University of Technology, Master Student
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6. Abstract (half page)

Research Theme: Study on Multi-vent based Adaptive Ventilation (MAV) for demand-oriented indoor environment
Representative Researcher (Affiliation): Weirong Zhang (BJUT)
Summary・Figures

1. A new ventilation end system with top air supply is proposed - Multi-vent Module-based Adaptive Ventilation (MAV). The system is based on a multi-vent module as The system is based on a multi-vent module, which can switch between supply and return air outlets to meet the adaptability of multiple scenarios. By applying CFD numerical simulation, a typical office space is established as an application scenario to investigate the impact of MAV on indoor air environment and thermal environment, and the following conclusions are obtained:

(1) The control of pollutant diffusion range and pollutant discharge rate of traditional MV are low in the face of indoor scene changes and pollutant source location changes, and its adaptability to such dynamic changes is weak.

(2) MAV can adapt well to dynamic changes by adjusting the MAV mode in the face of changes in the scene inside the classroom and changes in the location of the pollutant source, and shows excellent pollutant control ability and pollutant removal effect.

(3) The SVE4 of the lower sub-region corresponding to a certain module of MAV is higher than other sub-regions. It means that the zonal control function can be effectively implemented. This system can play an important role in non-uniform indoor environments oriented to local needs.

(4) Combined with the ADPI results, the overall thermal comfort of MAV is better than that of MV in all scenarios, and the thermal environment created by MAV is also better than that of MV in terms of local thermal comfort (PMV and DR). The PMV results of the applied MAV have more measurement points to meet the ISO 7730 Class B requirements, which is better than MV, and due to the scenario adaptation of MAV, it can effectively avoid The thermal discomfort of people near the air supply outlet can be effectively avoided due to the scene adaptation of MAV.